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ABSTRACT

By using ill-structured problems and examining problem- solving processes, this study was conducted to explore the nature of solving complex, multistep problems, focusing on how prior knowledge, problem-solving process utilization, and analogical problem solving are related to success. Twenty-four college students qualified to participate by virtue of 100% performance on the Test for Requisite Mathematical Knowledge. Stimulus problems were from "The Adventures of Jasper Woodbury," a video- based problem-solving series. Subjects worked independently to reach problem solutions and explained how they arrived at the solution. Two to four weeks later, subjects watched a second scenario with an analogous problem. Protocols were produced from the subjects' audio and video taped responses. Prior mathematical knowledge as defined in this study was necessary, but not solely sufficient for solving the two problems. Highly successful subjects spent more time on the problems than subjects in other levels, and minimally successful subjects spent the most time setting long-range plans and the least time setting immediate plans. It appears that the experience of dealing with the initial problem may have shaped how problem-solving processes were used on the later analogous problem. Engagement in the initial problem also appears to increase success on the analogous problem. (Contains 16 references.) (SLD)

The Influence of Prior Experience and Process Utilization in Solving Complex Problems

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Reports published in recent years have encouraged educators to provide students opportunities to solve problems similar to those found in everyday life. In turn, educators and materials developers are creating problems which are rather complex and embedded in realistic contexts. In such problems multiple steps are often required to reach a solution, multiple paths to a solution may exist, and the data and conditions necessary for solving them are not clearly stated.

Purpose of the Study

Research has documented that students perform poorly on complex, multiple-step problems (Cognition and Technology Group at Vanderbilt (CTGV), 1994; Goldman, et. al., 1991; Pellegrino et. al., 1991; and VanHaneghan et. al., 1992). Yet, the literature is incomplete in terms of why this is so. This may be because problem-solving research has tended to (a) utilize relatively well-structured problems, as opposed to ill-structured problems resembling those found in everyday situations, and (b) focus on problem-solving products (e.g., performance) as opposed to the processes leading to a solution.

By using ill-structured problems and examining problem-solving processes, this study was conducted to help close the gap between what is and is not yet known about the nature of solving complex, multiple-step problems. More specifically, the study was conducted to understand how prior knowledge, problem-solving process utilization, and analogical problem-solving are related to success at solving complex, multiple-step problems.

The study addressed three questions:

1. What are the similarities and differences among the problem-solving processes utilized by those achieving varying levels of success when solving a complex, multiple-step problem?

2. How are problem-solving processes and performance on one complex, multiple-step problem related to the processes and performance on a second, analogous problem?
3. How does recognition and application of a previously encountered complex, multiple-step problem influence performance on an analogous problem?

Methodology

There were three phases of data collection. In Phase I, the subjects were selected. First, thirty-one individuals enrolled in classes in the College of Education at a midwestern university volunteered to participate in the study. They were administered the Test for Requisite Mathematical Knowledge. The Test was designed to measure domain-specific knowledge (defined as concepts and skills requisite for solving the two stimulus problems). Twenty-four of the volunteers qualified as subjects by attaining 100% on the Test.

The stimulus problems used in this study were from The Adventures of Jasper Woodbury problem-solving series (CTGV, 1992). In this series, video-based scenarios tell a problem-centered story up to the point of resolution, at which time a main character is faced with a complex problem to solve. Problem solvers attempt to solve the problem by using information embedded in the video.

During Phase II, each subject independently viewed a video scenario. When presented with the problem-solving challenge, each subject worked independently to solve the problem. While working, each subject articulated what he/she was doing or thinking and why. Then, when finished, each subject was asked to explain how he/she arrived at the solution. After providing this solution summary, each subject was asked to respond to a set of questions (i.e., Have you ever had an opportunity to solve a problem similar to the one you just solved? If so, did you use

that similar problem to help you solve this Jasper problem?). Finally, each subject viewed the videodisc showing one possible solution and was asked to explain how his/her solution was similar to or different from the one viewed.

During Phase III, two to four weeks after each subjects first session, each subject watched a second scenario, which introduced the problem-solving context, analogous to the first problem, and presented the problem-solving challenge. Again, each subject worked independently to reach a solution while verbalizing his/her thoughts and actions, explained how he/she arrived at his/her solution, responded to the set of experience-related questions, viewed a possible solution, and discussed how it was similar to and different from his/her own.

The subjects' problem solving sessions were audio and video taped for later transcription and analysis. Protocols were produced from the transcribed tapes, supported by the researcher's and subject's notes. The protocols were then coded. The coding system used was based upon Schoenfeld's (1985) framework for interpreting problem-solving behaviors. To encompass the thoughts and activities generated as a result of the ill structured nature of the stimulus problems, Schoenfeld's system was modified and the resulting coding system was used to study the subjects' problem solving processes.

After coding the protocols, timelines were created showing the sequence and duration of the processes used to solve the problems. The timelines were later sorted according to the subjects' problem-solving performance levels. Given the nature of the complex problems (i.e., with multiple paths to the solution and multiple solutions possible), the subjects could achieve varying levels of success. Performance levels on the Initial and Analogous Problems were

determined according to the quality and quantity of the subjects' errors and omissions. Four levels resulted (Highly, Mostly, Moderately, and Minimally Successful).

Data Analyses

To answer the first research question, process utilization times were averaged across the data sets (Initial Problem and Analogous Problem) and performance levels. The averages were used to determine process utilization similarities and differences.

To answer the second question, the process utilization time results from the Initial and Analogous Problems were compared. For example, changes in performance from the Initial to the Analogous Problem were reported, along with the manner in which increases and decreases in process utilization times related to increases and decreases in performance.

To answer the third question, the subjects' responses to the experience-related questions were compiled and then compared. For example, responses were examined to see how the performances of subjects who recognized and applied an analogous experience compared to the performances of those who did not.

Results of the Study

As for the results in the area of prior knowledge, given that all of the subjects had attained 100% mastery on the Test for Requisite Mathematical Knowledge, but that success on both problems varied (as indicated by the spread across levels), it appears that prior mathematical knowledge as defined in this study was not solely sufficient for solving the two problems. The variance in performance levels indicated that some of the subjects may have failed to apply the domain-specific knowledge and skills to solve one or both of the problems, lacked or did not

utilize effective problem solving processes, and/or lacked or did not utilize knowledge and skills relevant to the problems but not addressed by the Test for Requisite Knowledge.

This finding that the subjects' prior knowledge was insufficient for solving complex, multiple-step problems supports previous literature addressing the role of knowledge in problem solving. For instance, Mayer (1982) documented that four types of knowledge (i.e., factual, schema, algorithmic, and strategic) may be necessary for successful problem-solving. Of these four knowledge types, the pretest mostly assessed factual knowledge (e.g., net income is considered profit) and algorithmic knowledge (e.g., net income equals revenue minus expenses). Schema and strategic knowledge weren't identified as prerequisites by the creators of the stimulus materials (CTGV, 1992) and therefore were not directly assessed. For example, the pretest did not determine the subjects' possession of knowledge pertaining to the context in which the problem was embedded (i.e., schema for the recycling center). Similarly, the pretest did not measure the subjects' possession of strategic knowledge pertaining to "how to" arrive at a final solution or solutions to subproblems.

Process Utilization

In terms of process utilization results, in addressing the first research question, the findings provided a general indication of how the subjects reached solutions to complex, multiple-step problems and highlighted process utilization differences distinguishing those who achieved optimal success from those who did not. For example, on the Initial Problem the subjects in all performance levels:

- spent the greatest amount of time exploring and operating and the least amount of time reading and analyzing the problem-solving challenge; and

- spent more time setting immediate than long range plans.

Process utilization differences on the Initial Problem included the facts that:

- the times required to reach a solution varied across performance levels, with Highly Successful subjects spending considerable more time than subjects in other levels;
- Highly Successful subjects also concentrated their reading time early in the problem-solving session, engaged in extended periods of explore activity in the beginning of the problem-solving session, and engaged in "quality control" activities between their initial and final completion proclamations; and,
- Minimally Successful subjects tended to engage in only one problem-solving process at a time unlike subjects in the more successful levels who exhibited multi-tasking efficiencies and spent a relatively high amount of time engaged in immediate planning and a relatively low amount of time engaged in long range planning.

On the Analogous Problem, the subjects in all performance levels:

- spent the greatest amount of time exploring, operating, and recording, and the least amount of time reading and analyzing the problem-solving challenge;
- spent less time in long range planning than immediate planning; and,
- showed evidence of multi-tasking.

The major distinctions found among the levels included the facts that:

- the times required to reach a solution varied across performance levels with Minimally Successful subjects requiring the least amount of time; and,
- Minimally Successful subjects spent the greatest amount of time setting long range plans and the least amount of time setting immediate plans.

In discussing the findings pertaining to the first research question, although the subjects in all of the performance levels used the various problem-solving processes similarly in a quantitative sense (e.g., extensive utilization of explore and operate, and less extensive utilization of read and analyze), process utilization distinctions between Highly and Minimally Successful subjects were noted. For example, on the Initial Problem, Highly Successful subjects demonstrated a "quality control" mechanism between the initial and final completion proclamations, as they monitored their work and adjusted their solutions accordingly. Such activity was not demonstrated by Minimally Successful subjects.

The quality control finding supports research (e.g., Schoenfeld, 1985) documenting the role of self-regulation (how one uses what is known, rather than simply what one knows) in successful problem solving. For instance, Schoenfeld (1985) showed that although subjects had enough content knowledge to solve a geometry problem, they were unsuccessful in reaching a solution because they failed to self-regulate. On the other hand, when progress was monitored and adjusted by other subjects, as opposed to continuing to engage in a "wild goose chase," greater success was achieved.

In addressing the second question, overall, the findings revealed that from the Initial Problem to the Analogous Problem:

- the number of Highly Successful subjects increased considerably with three Highly Successful subjects on the Initial Problem versus nine on the Analogous Problem;
- the majority of subjects (N=21) either increased levels or remained in the same level; only a small number of subjects (N=3) showed a decrease in levels from problem to problem; and,

- the total average time required to reach a solution decreased from 52 to 39 minutes, and became more similar across the levels.

Further, the findings revealed that some of the problem-solving process trends noted on the Initial Problem disappeared, became more inclusive, or were reversed from the Initial to the Analogous Problem. For example, on the Initial Problem, the solution time between Highly Successful and Minimally Successful subjects corresponded with performance (i.e., the group achieving the highest performance spent the greatest amount of time attempting to reach a solution, and the group achieving the lowest performance spent the least amount of time). However, such correspondence between performance and time to reach a solution was not evident on the Analogous Problem.

Additionally, two trends emerged among the read and explore processes on the Initial Problem. On the Initial Problem, Highly Successful subjects concentrated their read activity and engaged in extended explore activity at the beginning of the problem, whereas subjects in other levels did not. However, these trends were not found on the Analogous Problem.

Two explanations may account for these disappearing trends. First, previous research (CTGV, 1994; Goldman et al., 1991; Pellegrino et al., 1991, and VanHaneghan et al., 1992) reported that experience solving complex, multiple-step problems brings greater opportunities for future success. Experience from the Initial to the Analogous Problem, possibly leading to greater problem-solving efficiencies, may have accounted, in part, for the disappearance of trends.

Second, although this study did not work within the expert Expert-Novice framework as such, the Expert-Novice literature provides insight as to why these trends (i.e., concentration of reading and explore activities in the beginning of the problem) disappeared. For example, Larkin

(1980) noticed that experts performed a "qualitative analysis" before generating equations for solving a problem. It is possible that Highly Successful subjects' concentration of read and explore in the beginning of the problem allowed for qualitative analysis to occur. Further, perhaps the process of carrying out a qualitative analysis prior to engaging in quantitative activities (e.g., "operating") provided Highly Successful subjects with much of the necessary information for seeing the problem through.

As an example of a trend that became more inclusive, on the Initial Problem only subjects in more successful levels exhibited multi-tasking efficiencies, but on the Analogous Problem, subjects in all four levels did so. Although this specific multi-tasking finding may not be documented in previous research, it is supported by studies (CTGV, 1994; Goldman et al., 1991; Pellegrino et al., 1991, and VanHaneghan et al., 1992) documenting the positive role experience plays in solving complex problems. It is possible that multi-tasking was due to efficiencies gained during the encounter with the Initial Problem.

As an example of a trend reversal, relative to the other levels on the Initial Problem, Minimally Successful subjects spent a disproportionately high amount of time in immediate planning and a disproportionately low amount of time in long range planning. However, on the Analogous Problem, this trend was reversed; Minimally Successful subjects spent the least amount of time setting immediate plans and the greatest amount of time setting long range plans. Again, these planning patterns may have shifted as experience was gained from the Initial Problem to the Analogous Problem.

Goldman et al. (1991) found that the subjects in their study were more likely to generate and solve related subproblems when subgoals were made explicit for them. By prompting their

subjects to generate subgoals, the subjects considered a greater amount of the necessary components for reaching a solution.

In the current study, perhaps the video solution played after the subjects completed the Initial Problem provided the subjects with a model that facilitated greater inclusion of the necessary components for reaching a solution to the Analogous Problem. Thus, the greater amount of time that the Minimally Successful subjects spent in long range planning on the Analogous Problem may be explained by the fact that these subjects had an opportunity to learn how one plans for solving such problems. Further, the Minimally Successful subjects may have followed the model provided in the video, which may have accounted for their increased long range planning activities on the Analogous Problem.

In sum, while these and other trend disappearances, changes, and reversals might be dismissed as chance occurrences, a more insightful explanation is that the experience of dealing with the Initial Problem may have shaped how the problem-solving processes were used on the Analogous Problem. Furthermore, given that the vast majority of subjects (N=21) may have either remained the same or improved their performance from the Initial Problem to the Analogous Problem, it appears that engagement in the Initial Problem contributed to increased success on the Analogous Problem.

Analogical Problem-Solving Experience

In addressing the third research question, the majority of subjects (i.e., 15 out of 24 subjects on the Initial Problem, and 16 out of 24 subjects on the Analogous Problem) recognized having had similar problem-solving experiences. However, few of those who recognized having

had these experiences (i.e., 3 out of 15 subjects on the Initial Problem, and 2 out of 16 subjects on the Analogous Problem) reported having applied them to help solve the problem at hand.

Next, after solving the Analogous Problem, the subjects who reported having had a similar life experience were concentrated in the Highly and Mostly Successful levels, whereas the subjects who reported having had a similar experience solving the Initial Problem were concentrated in the Moderately Successful level. However, although the results indicated that greater problem-solving performance may have been influenced by similar life experiences, these life experiences were just as unlikely to have been applied as experiences solving the Initial Problem.

Additionally, of the group increasing performance levels (N=11), only two out of eight subjects applied a similar experience (i.e., one subject applied a life experience, and one applied the experience solving the Initial Problem). Of the groups decreasing performance levels (N=3) or remaining Highly Successful (N=3) from problem to problem, none of the subjects applied a similar experience to help solve the Analogous Problem.

Collectively, these data support the notion that performance was not apparently influenced by recognition and subsequent application of a similar problem-solving experience. They also support previous analogical problem-solving research (Gick and Holyoak, 1980, 1983; Holyoak and Koh, 1987) showing that a gap between noticing and applying analogies existed. After solving the Analogous Problem, only sixteen subjects recognized having had previous related experiences, in spite of the many surface similarities between the Initial and the Analogous Problems. Even more problematic, only one subject reported using the content encountered in the Initial Problem to help solve the problem.

Gick and Holyoak (1980, 1983) suggested that there are three components that influence analogical transfer from initial to analogous problems. First, although individuals may fail to notice the relevance of analogies, if given a hint they are more apt to apply them. Second, the more similar a source (e.g., Initial Problem) and a target problem (e.g., Analogous Problem), the more likely transfer will occur. Third, exposure to multiple source problems increases the likelihood that transfer will occur. Considering these components, the majority of subjects may have failed to apply the Initial Problem to the Analogous Problem because they were given no "hint" to do so, did not realize the similarity between the problems, and/or did not have multiple sources from which to draw.

An alternative explanation as to why the majority of subjects in the current study failed to apply the content of one problem to help them solve a similar problem is related to the fact that they were faced with solving ill-structured problems. As discussed earlier, much of the analogical problem-solving literature is comprised of research using well-structured stimulus problems. The ill-structured nature of complex, multiple-step problems and the realistic contexts in which the problems were embedded may have offered conditions for which it was difficult to apply analogies for reaching a solution.

Further, as pointed out above, when answering the two experience-related questions which followed each problem, several Highly and Mostly Successful subjects cited life experiences as similar. This suggests that analogous life experiences are possibly more helpful than formally developed, analogous experiences for solving complex, multiple-step problems.

The following points provide an explanation as to why this might be. Researchers (e.g., Resnick, 1987) have documented the differences between in-school and out-of-school learning

(e.g., individual vs. shared cognition; symbol manipulation vs. contextualized reasoning; and, generalized learning vs. situation specific competencies). Out-of-school learning experiences are those that others (e.g., Brown, Collins, & Duguid, 1989) have referred to as "authentic." Authentic tasks have been defined as "the ordinary practices of a culture (Brown, Collins, & Duguid, 1989 p. 34)." As such, they are coherent, meaningful, and purposeful activities. Brown et al. have explained that when authentic activities are transferred to the classroom, they simply become classroom tasks.

Because the stimulus problems used in the current study were not situated in an actual real-world experience, it is likely that the majority of subjects associated the problems with school activities and thus did not make the connection to their analogous life experiences. This finding raises questions about the ability of the formally developed stimulus problems to provide an effective anchor for solving such problems.

Conclusions and Recommendations

In conclusion, the results of the current study revealed the following:

- Domain specific knowledge was necessary but not solely sufficient for attaining optimal success when solving complex problems.
- The utilization of certain problem-solving processes (e.g., when certain processes were employed and the amount of time given to them) facilitated optimal success on complex, multiple-step problems.
- Experience solving complex, multiple-step problems provided opportunity for greater future success.

- The ill-structured nature of complex, multiple-step problems and the realistic contexts in which the problems were embedded offered conditions for which it was difficult to apply analogies for reaching a solution.

The results present several implications for research and practice. First, due to the limited amount of research informing how complex, multiple-step problems are solved, additional research employing ill-structured stimulus problems is needed. This research should continue to investigate the roles of prior knowledge (of various types), process utilization (quantity distribution and quality), and experience in solving complex problems.

More specifically, in the area of analogical problem solving, practitioners extending opportunities for students to solve complex problems should consider providing them with authentic experiences resembling those found out-of-school. Experiences such as realistic simulations of activities similar to those needed on upcoming problems may serve as effective anchors providing initial problem-solving experiences that may facilitate transfer to subsequent problem-solving situations. This, in turn may increase problem understanding and allow for greater problem-solving success. Researchers may be interested in studying the effects of simulation activities on the application of analogical reasoning. More specifically, researchers might compare the effects of using simulations with anchors that have been formally developed.

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